Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
Designing CBL Systems for Complex Domains using Problem Transformation and Fuzzy Logic

A thesis presented in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Computer Science

at Massey University, Palmerston North, New Zealand.

Selvarajah Mohanarajah
2007
Acknowledgement

This research would not have been possible without the support, inspiration, and enthusiasm of my supervisors, Associate Professors R. Kemp and E. Kemp. They gave me the appropriate guidance as well as unbounded freedom, whenever it was necessary. A special thanks to Ray for keeping me as an assistant lecturer for six long years at the computer science division of IIST. I am also grateful to Janina for her support during my final months at Massey. I would also like to thank my former colleagues at IIST including the office staff and technical support staff who has extended their goodwill in numerous ways.

It was Loji, my late wife, whose constant understanding, endless patience, encouragement and love made this mission achievable. While I was studying- during our entire married life- she was awaiting to see my success. It is to her, I dedicate this work. I am also thankful to my daughters Archu and Mathu for their sacrifice and understanding when it was most required. Finally, I am forever indebted to my mother, brothers, Loji’s family and our friends, without their unflinching encouragement, this thesis might not have been appeared in its present form.
Publications

The following publications are made out of this research.


dedicated to
LOJI
Abstract

Some disciplines are inherently complex and challenging to learn. This research attempts to design an instructional strategy for CBL systems to simplify learning certain complex domains. Firstly, problem transformation, a constructionist instructional technique, is used to promote active learning by encouraging students to construct more complex artefacts based on less complex ones. Scaffolding is used at the initial learning stages to alleviate the difficulty associated with complex transformation processes. The proposed instructional strategy brings various techniques together to enhance the learning experience. A functional prototype is implemented with Object-Z as the exemplar subject. Both objective and subjective evaluations using the prototype indicate that the proposed CBL system has a statistically significant impact on learning a complex domain.

CBL systems include Learner models to provide adaptable support tailored to individual learners. Bayesian theory is used in general to manage uncertainty in Learner models. In this research, a fuzzy logic based locally intelligent Learner model is utilized. The fuzzy model is simple to design and implement, and easy to understand and explain, as well as efficient. Bayesian theory is used to complement the fuzzy model. Evaluation shows that the accuracy of the proposed Learner model is statistically significant. Further, opening Learner model reduces uncertainty, and the fuzzy rules are simple and resemble human reasoning processes. Therefore, it is argued that opening a fuzzy Learner model is both easy and effective.

Scaffolding requires formative assessments. In this research, a confidence based multiple test marking scheme is proposed as traditional schemes are not suitable for measuring partial knowledge. Subjective evaluation confirms that the proposed schema is effective. Finally, a step-by-step methodology to transform simple UML class diagrams to Object-Z schemas is designed in order to implement problem transformation. This methodology could be extended to implement a semi-automated translation system for UML to Object Models.
# Contents

Acknowledgement.............................................................................................................. i
Publications ......................................................................................................................... iii
Abstract .............................................................................................................................. vii
Contents ............................................................................................................................. ix
List of Figures ...................................................................................................................... xiii
List of Tables ......................................................................................................................... xv

Chapter 1  Introduction ........................................................................................................ 1
  1.1 Background .................................................................................................................. 1
  1.2 Research Questions .................................................................................................... 2
  1.3 Objectives ................................................................................................................... 5
  1.4 Scope ......................................................................................................................... 6
  1.5 Methodology ............................................................................................................. 6
  1.5 Thesis Outline .......................................................................................................... 7

Chapter 2  Computer Based Learning Systems ................................................................ 9
  2.1 Introduction................................................................................................................ 9
  2.2 Learning Theories – An Overview ........................................................................... 10
    2.2.1 Behaviourism ........................................................................................................ 10
    2.2.2 Cognitivism .......................................................................................................... 10
    2.2.3 Constructivism ..................................................................................................... 12
    2.2.4 Beyond Situated Cognition- Academic Knowledge ............................................ 13
  2.3 CBL Systems – An Overview .................................................................................. 14
    2.3.1 From CAI to ICAI ............................................................................................... 14
    2.3.2 From ICAI to ITS ............................................................................................... 14
    2.3.3 From ITS to ILE ................................................................................................. 16
    2.3.4 From ILE to Bi-modus Learning Environment ................................................ 17
    2.3.5 Collaborative Learning Systems ...................................................................... 17
    2.3.6 E- Learning .......................................................................................................... 18
  2.4 Learning Theories and CBL Systems ...................................................................... 18
    2.4.1 Constructionism and Discovery Worlds ............................................................ 19
    2.4.2 Bi-modus Learning Environment ...................................................................... 20
  2.5 Motivation and Learning ......................................................................................... 21
  2.6 Cognitive Apprenticeship Model ............................................................................. 23
    2.6.1 Scaffold ............................................................................................................... 23
  2.7 Authoring Systems .................................................................................................... 24
  2.8 Pedagogical Action Selection .................................................................................. 25
    2.8.1 Curriculum Sequencing ..................................................................................... 26
    2.8.2 Feedback ............................................................................................................. 26
  2.9 Learner models .......................................................................................................... 28
    2.9.1 Uncertainty in Learner modelling ....................................................................... 30
    2.9.2 Opening Learner models ................................................................................... 33
  2.10 Assessment in CBL systems - The Role of MC test .............................................. 35
    2.10.1 Rewarding Partial Knowledge ......................................................................... 37
  2.11 Summary ................................................................................................................ 38

Chapter 3  CBL Systems for Programming and Formal Methods .................................... 41
## Contents

3.1 Introduction .................................................................................................................. 41
3.2 Teaching Systems for Programming ............................................................................ 42
  3.2.1 Overview .............................................................................................................. 42
  3.2.2 Challenges and Drawbacks ................................................................................... 42
  3.2.3 CBL Systems for Programming ........................................................................... 43
3.3 Formal Methods in Software Engineering .................................................................... 48
  3.3.1 Overview .............................................................................................................. 48
  3.3.2 Formal Method Tools .......................................................................................... 50
  3.3.3 Teaching and Learning Formal Methods .............................................................. 52
3.4 Teaching Systems for Formal Methods ........................................................................ 53
  3.4.1 Formal Method Tools for Teaching ...................................................................... 53
  3.4.2 CBL Systems for Formal Methods ....................................................................... 54
3.5 Summary ....................................................................................................................... 56

4.2 Learning by Transformation ......................................................................................... 58
  4.2.1 Problem Transformation ...................................................................................... 59
4.3 Transforming UML models to Object-Z Specifications ............................................. 61
  4.3.1 Requirement Specification - Overview .................................................................. 62
  4.3.2 UML Overview ................................................................................................... 62
  4.3.3 Object-Z Overview .............................................................................................. 65
  4.3.4 Transforming Semi-formal models to Formal models – An Overview .............. 68
  4.3.5 Formalizing UML models .................................................................................... 73
  4.3.6 Transforming UML models to Object-Z ............................................................... 75
4.4 Summary ....................................................................................................................... 83

5.1 Introduction ................................................................................................................... 85
5.2 Survey on a Formal Method (Z) and a Tool (Formalizer) .......................................... 86
5.3 Designing an Instruction Strategy ................................................................................ 88
  5.3.1 Problem Domain .................................................................................................. 88
  5.3.2 Scaffolding Abstraction ....................................................................................... 90
  5.3.3 Case Study Approach .......................................................................................... 92
5.4 A Four Phase Instructional Model ................................................................................ 93
  5.4.1 The Four-Phases of FoPSI model ......................................................................... 94
5.5 Overview of LOZ .......................................................................................................... 96
5.6 Domain Model ............................................................................................................. 97
  5.6.1 Mental States ....................................................................................................... 99
  5.6.2 Multiple Choice tests for Formative Assessment ................................................ 102
  5.6.3 Misconceptions and Feedback .............................................................................. 103
5.7 MC Tests as Scaffolding Blocks .................................................................................. 105
  5.7.1 Drawback of Traditional MC test ........................................................................ 105
  5.7.2 Designing a Confidence-Based MC Test Schema ................................................. 106
5.8 Mentor Model .............................................................................................................. 110
  5.8.1 Pedagogical Action Selection .............................................................................. 110
  5.8.2 PAS Tables for Traditional MC tests .................................................................. 111
  5.8.3 Fully Learner-Controlled Environment ............................................................... 115
5.9 Refinement Unit ......................................................................................................... 117
5.10 Summary ..................................................................................................................... 118
Chapter 6 _Designing a Fuzzy Learner Model_ .............................................................. 121

6.1 Introduction ........................................................................................................... 121
6.2 Learner Model Complexity .................................................................................. 122
   6.2.1 Locally-intelligent Learner Model ....................................................................... 122
6.3 A Simple Learner Model ..................................................................................... 123
6.4 Determining Pedagogical Actions under Uncertainty ......................................... 128
   6.4.1 Uncertainty Handling ....................................................................................... 129
6.4.2 Adaptable Scaffolding ...................................................................................... 130
6.4.3 Fuzzification, Rule Propagation and Defuzzification ....................................... 135
6.5 Predicting the Strength of Mental States ............................................................. 139
   6.5.1 Dynamic Relations ......................................................................................... 141
6.6 Updating the Strength of Mental States ............................................................... 144
6.7 Initialising Strength of Mental States ................................................................... 151
6.8 Determining General Learning Ability ................................................................ 152
6.9 Opening Learner Models .................................................................................... 155
   6.9.1 Opening Mentor Model .................................................................................. 158
6.10 Summary and Conclusion .................................................................................. 159

Chapter 7 _Prototype – Design and Implementation_ ................................................... 161

7.1 Introduction .......................................................................................................... 161
7.2 Scope of the Prototype ......................................................................................... 162
7.3 Implementation Issues ......................................................................................... 163
7.4 System Architecture ............................................................................................ 163
7.5 Domain Model Design ......................................................................................... 167
7.6 Learner Model Design ........................................................................................ 170
7.7 Fuzzy Model for Uncertainty Handling ............................................................... 171
7.8 Mentor Model Design ......................................................................................... 174
7.9 Database Design .................................................................................................. 176
7.10 Interface Design ................................................................................................ 182
7.11 Opening the Learner Model .............................................................................. 186
7.12 Summary ............................................................................................................ 187

Chapter 8 _Evaluation and Discussion_ ........................................................................ 189

8.1 Introduction .......................................................................................................... 189
8.2 Research Claims .................................................................................................. 190
8.3 Evaluation Strategies .......................................................................................... 191
   8.3.1 Evaluating the System: Empirical Study ......................................................... 192
   8.3.2 Evaluating the Learner Model: Log Files ....................................................... 195
   8.3.3 Questionnaire .................................................................................................. 198
   8.3.4 Evaluating CBM schema ............................................................................... 199
8.4 Pilot Study ............................................................................................................ 201
8.5 Evaluation Process .............................................................................................. 202
   8.5.1 Empirical Study .............................................................................................. 202
   8.5.2 Log Files for Learner Model Accuracy ......................................................... 203
8.6 Results and Discussion ....................................................................................... 204
   8.6.1 Hypothesis– 1: Effectiveness of LOZ .............................................................. 204
   8.6.2 Hypothesis – 2: Accuracy of the Learner Model .......................................... 208
   8.6.3 Evaluating CBM Schema ............................................................................... 211
   8.6.4 Subjective Analysis ....................................................................................... 212
   8.6.5 Summary of Results & Discussion ............................................................... 215
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Stages of an Information Processing Model (after Reed 2003, p.71))</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Intelligent Tutoring Systems (after Shute et al (1995))</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Types of Motivation (Ryan et al., 2000, p. 72)</td>
<td>22</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>A Decision-Making Framework for Feedback (Mason et al. 1999)</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>(a) Learner Model Usage (Mayo 2001) (b) Uncertainty Escalation</td>
<td>31</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>A Z Specification for Credit Card Application</td>
<td>49</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Z-EVES environment, a formal method tool</td>
<td>51</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Formalizer Feedback</td>
<td>51</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Use case Model: Key- Room Case Study</td>
<td>63</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Class Diagram: Key- Room Case Study</td>
<td>64</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Operation Specifications: Key- Room Case Study</td>
<td>65</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Sequence Diagram: Key- Room Case Study</td>
<td>65</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Structure of a Class Schema</td>
<td>66</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>Class Schema for Room</td>
<td>68</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>Class Schema for Key</td>
<td>69</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Value Semantics and Identity of an Object</td>
<td>76</td>
</tr>
<tr>
<td>Figure 4.9</td>
<td>Formalizing Association: Local</td>
<td>78</td>
</tr>
<tr>
<td>Figure 4.10</td>
<td>Formalizing Association: Recursive</td>
<td>79</td>
</tr>
<tr>
<td>Figure 4.11</td>
<td>Formalizing Association: Central</td>
<td>80</td>
</tr>
<tr>
<td>Figure 4.12</td>
<td>Formalizing Association: Variations</td>
<td>80</td>
</tr>
<tr>
<td>Figure 4.13</td>
<td>The Notion of Environment in Object-Z</td>
<td>82</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Architecture of LOZ</td>
<td>96</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Lesson Organization – An Example</td>
<td>99</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>A Sub-concept and related Mental States</td>
<td>99</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Mental States- Causal Relations</td>
<td>101</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>Overview of the Domain Model in LOZ</td>
<td>104</td>
</tr>
<tr>
<td>Figure 5.6</td>
<td>Interface for Marking Confidence</td>
<td>107</td>
</tr>
<tr>
<td>Figure 5.7</td>
<td>The notion of distance used in CBM test</td>
<td>108</td>
</tr>
<tr>
<td>Figure 5.8</td>
<td>Fuzzy Membership Functions for Performance (P)</td>
<td>114</td>
</tr>
<tr>
<td>Figure 6.1</td>
<td>Lesson Organization (including Mental States)</td>
<td>124</td>
</tr>
<tr>
<td>Figure 6.2</td>
<td>Fuzzy Membership Functions for SMS</td>
<td>132</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Fuzzy Membership Functions for PAS</td>
<td>133</td>
</tr>
<tr>
<td>Figure 6.4</td>
<td>Causal Relations for PAS</td>
<td>134</td>
</tr>
<tr>
<td>Figure 6.5</td>
<td>Defuzzification, using Larsen’s Product Rule</td>
<td>138</td>
</tr>
<tr>
<td>Figure 6.6</td>
<td>Causal Relations for SMS and L</td>
<td>140</td>
</tr>
<tr>
<td>Figure 6.7</td>
<td>Dynamic Relations</td>
<td>143</td>
</tr>
<tr>
<td>Figure 6.8</td>
<td>Modified Causal Relations</td>
<td>146</td>
</tr>
<tr>
<td>Figure 6.9</td>
<td>Dynamic Relations for GLA</td>
<td>153</td>
</tr>
<tr>
<td>Figure 7.1</td>
<td>JDatastore Explorer Environment</td>
<td>164</td>
</tr>
<tr>
<td>Figure 7.2</td>
<td>Interface for Editing Table in JDataStore</td>
<td>164</td>
</tr>
<tr>
<td>Figure 7.3</td>
<td>Layered Architecture</td>
<td>165</td>
</tr>
<tr>
<td>Figure 7.4</td>
<td>Log-in Process: A Happy Day Scenario</td>
<td>166</td>
</tr>
<tr>
<td>Figure 7.5</td>
<td>Class Diagram for Domain Model – Concepts</td>
<td>167</td>
</tr>
<tr>
<td>Figure 7.6</td>
<td>A Sub-concept: Visibility List</td>
<td>168</td>
</tr>
<tr>
<td>Figure 7.7</td>
<td>Class Diagram for Domain Model – Mental States and Concepts</td>
<td>169</td>
</tr>
<tr>
<td>Figure 7.8</td>
<td>A MC Test &amp; Answering Interface</td>
<td>169</td>
</tr>
<tr>
<td>Figure 7.9</td>
<td>Class Diagram for Learner Model – Learner and GLA</td>
<td>170</td>
</tr>
<tr>
<td>Figure 7.10</td>
<td>Class Diagram for Learner Model – Learner, SMS and PAS</td>
<td>171</td>
</tr>
<tr>
<td>Figure 7.11</td>
<td>Uncertainty Handling – Fuzzy Model</td>
<td>172</td>
</tr>
<tr>
<td>Figure 7.12</td>
<td>Code for a Fuzzification Process</td>
<td>173</td>
</tr>
<tr>
<td>Figure 7.13</td>
<td>Code for Fuzzy rule application process</td>
<td>173</td>
</tr>
</tbody>
</table>
Figures

Figure 7.14a Sequence Diagram for finding PAS (continues in Figure 7.14b) .................................................. 175
Figure 7.14b Sequence Diagram for finding PAS (continued from Fig 7.14a) .................................................. 176
Figure 7.15 Designing Associations ............................................................................................................... 177
Figure 7.16 An Overall ER Diagram ............................................................................................................. 177
Figure 7.17a Relational Tables – Concepts and Learner .................................................................................. 177
Figure 7.17b Relational Tables – Learners ...................................................................................................... 178
Figure 7.18 Offline Table Definitions ............................................................................................................ 179
Figure 7.19a Code for the Abstract Parent class of Database Brokers ............................................................ 180
Figure 7.19b Code for a Database Broker ...................................................................................................... 181
Figure 7.19c Code for the Cache Access ........................................................................................................ 180
Figure 7.20a A PERSONA (Sam) .................................................................................................................... 181
Figure 7.20b A Happy day Scenario – New Returning Learner ....................................................................... 182
Figure 7.20c A Happy day Scenario – Learner ................................................................................................ 183
Figure 7.21 Screen Navigation ........................................................................................................................ 184
Figure 7.22 New Learner Screen .................................................................................................................... 185
Figure 7.23 Learner Model Estimates ............................................................................................................. 186
Figure 7.24 Explaining Learner Model Behaviour ......................................................................................... 186
Figure 8.1 Fuzzy Membership Functions for Performance .............................................................................. 196
Figure 8.2 Causal Relations for PAS ............................................................................................................. 197
Figure 8.3 MC Test Answering Interface – CBM Strategy ............................................................................ 200
Figure 8.4 Pre Vs Post-test scores- Bar Chart ................................................................................................. 204
Figure 8.5 Pre Vs Post-test scores- Basic Statistics ......................................................................................... 205
Figure 8.6 Power of the Experiment .............................................................................................................. 207
Figure 8.7 Statistics for Tests - Ver. 1 Vs Ver.2 ............................................................................................... 208
Figure 8.8 Pearson Correlation Co-efficient ................................................................................................. 209
Figure 8.9 Performance Prediction Mechanism (two levels) ......................................................................... 210
Figure 8.10 Performance Prediction Mechanism (three levels) ..................................................................... 211
Figure 9.1 Case Study ....................................................................................................................................... 221
Figure 9.2 Scaffolding Level-I: Support for Syntax .......................................................................................... 224
Figure 9.3 Challenge: Specifying Functional Abstraction ............................................................................. 226
Figure 9.4 Interactive Help on Semantics ....................................................................................................... 226
Figure 9.5 Challenge: Functional Abstraction .............................................................................................. 227
Figure 9.6 Challenge: Data Specification and Functional Abstraction ......................................................... 227
Figure 9.7 Challenge: Data & Functional Abstraction .................................................................................. 228
Figure 9.8 A portion of Domain Model for Phase-II ..................................................................................... 231
Figure 9.9 Dynamic Causal Relations for Phase-II ...................................................................................... 230
Figure 9.10 Causal Relations for Task Sequencing in Phase-II ....................................................................... 231
Figure 9.11 Predicting Performance on a Testable Concept ........................................................................... 232
Figure 9.12 Interactive Help on Semantics .................................................................................................... 234
Figure 9.13 Sequence Diagram for the Main Use case .................................................................................. 242
Figure 9.14 Class Schema Generated for Room ............................................................................................ 243
Figure 9.15 Class Diagram ............................................................................................................................ 243
Figure 9.16 State Schemas for Room and Key ............................................................................................... 244
Figure 9.17 Operation Partially Completed .................................................................................................. 244
Figure 9.18 Class Schema for Key ............................................................................................................... 245
Figure 9.19 Alternate Use case Realization: Sequence Diagram ..................................................................... 246
Figure 9.20 Operations of an Alternate Schema ........................................................................................... 246
<table>
<thead>
<tr>
<th>Table 2.1 Feedback Types (based on (Mason et al. 1999))</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5.1 Pedagogical Actions for Correct Answers</td>
<td>111</td>
</tr>
<tr>
<td>Table 5.2 Pedagogical Actions for Incorrect Answers</td>
<td>112</td>
</tr>
<tr>
<td>Table 5.3 Pedagogical Actions for Medium Answers</td>
<td>115</td>
</tr>
<tr>
<td>Table 6.1 SMS and Pedagogical Actions</td>
<td>127</td>
</tr>
<tr>
<td>Table 6.2 Fuzzy Rules for PAS</td>
<td>134</td>
</tr>
<tr>
<td>Table 6.3 Fuzzy Rules for L (Degree of Learning)</td>
<td>140</td>
</tr>
<tr>
<td>Table 6.4 Fuzzy Rules for the Dynamic Variable SMS</td>
<td>143</td>
</tr>
<tr>
<td>Table 6.5 Conditional Probability Distribution (SMS&amp;D)</td>
<td>147</td>
</tr>
<tr>
<td>Table 6.6 Conditional Probabilities and Likelihood Ratios (SMS&amp;D)</td>
<td>150</td>
</tr>
<tr>
<td>Table 6.7 Conditional Probabilities (for Dynamic Relation)</td>
<td>153</td>
</tr>
<tr>
<td>Table 6.8 Conditional Probabilities and Likelihood Ratios (GLA&amp;SMS)</td>
<td>154</td>
</tr>
<tr>
<td>Table 8.1 Fuzzy Rules for Performance</td>
<td>197</td>
</tr>
<tr>
<td>Table 8.2 Subjective Evaluations – Questionnaire</td>
<td>199</td>
</tr>
<tr>
<td>Table 8.3 Difference (post-test – Pre-test) Statistics</td>
<td>205</td>
</tr>
<tr>
<td>Table 8.4 Learner Model Accuracy – Statistics</td>
<td>210</td>
</tr>
<tr>
<td>Table 8.5 Subjective Evaluation – Response Statistics</td>
<td>214</td>
</tr>
<tr>
<td>Table 9.1 Fuzzy Rules for Predicting Performance</td>
<td>231</td>
</tr>
<tr>
<td>Table 9.2 Fuzzy Rules for Task Sequencing in Phase-II</td>
<td>231</td>
</tr>
<tr>
<td>Tables 9.3 Fuzzy Rules for Interactive Problem Solving Support</td>
<td>233</td>
</tr>
<tr>
<td>Tables 9.4 Fuzzy Rules for Feedback during Problem Solving</td>
<td>233</td>
</tr>
</tbody>
</table>